A Brief on the Arc-Fault Circuit Interrupter

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ABSTRACT

Unwanted and uncontrolled electrical arcs are associated with fire causes in residences and elsewhere. A technology has been developed that will recognize an arc in a 120 V, ac system and signal the opening of the circuit by a disconnecting means such as a circuit breaker. This technology is capable of distinguishing between normal-operation arcs, such as might exist at the brushes of a motor, and hazardous arcs, such as from damaged conductor insulation. This paper discusses some of the basis for the development of the technology. It also discusses elements of the product certification standard to identify what is required of an arc-fault circuit interrupter (AFCI).

WHY A NEED FOR ARC FAULT DETECTION?

An electric arc is a luminous discharge of electricity across an insulating medium which exists at temperatures between 5,000 and 15,000 F at its center. Energy from the arc produces high pressures at its center which result in expulsion of hot, ionized gas and perhaps small, molten metal particles from electrodes. Nearby materials which may be exposed to the heat of the arc or its expelled gas may ignite. Any material on which molten metal particles fall may ignite. In other words, arcing conditions are potential fire causes when they are uncontrolled.

When electrical wiring or equipment is damaged, improperly installed or misused, a hazardous arc may occur under a number of conditions. These unexpected and unwanted arcs are responsible for causing a number of accidental fires. The National Fire Protection Association calculates that there are 40,000 fires resulting in 370 deaths annually in the United States due to electrical distribution system causes. [1]

Using data available from a major insurance company, the author has estimated that over one-third of these fires are from arcing fault causes. This estimate is reinforced by descriptions of fires in a 1987 report by the Consumer Product Safety Commission (CPSC). [2] As a reasonableness check, one may realize that there are only two primary causes of fires from electricity. One is thermal from overheated conductors or equipment, and the other is arcing. Thermal conditions that damage electrical insulation can lead to arcing.

ARCING-FAULT CAUSES OF FIRES

Some of the conditions in which arcs occur as potential fire causes are:

Pinched or pierced insulation on construction wire or cords, such as from staples or other fasteners.

.Cracked insulation on wire or cords from age, heat, chemical erosion or bending stress.

Overheated wire or cords.

Loose or improper connections.

Frayed or ruptured extension or appliance cords.

Damaged appliances in which support or insulation for energized electrical parts is impaired.

Wire or cords touching vibrating metal.

Moisture or contaminants between conductors of different voltage.

To gain an idea of how fires actually relate to arcing occurrences, this section looks at some wire and equipment that caused fires or almost caused fires.

Pierced insulation. Figure 1 shows evidence collected from a fire occurrence by the Bureau of Fire Prevention in Cedar Rapids, IA. The three pieces of No. 12 AWG, Type TW copper wire had been installed in a length of flexible metallic conduit in the ceiling. Firemen disconnected the installation after a call reporting heavy smoke. The overcurrent protective device (OCPD) had not opened indicating that current was not high enough or sustained long enough to cause opening. Although there is some melting of insulation on all three wires, a direct short circuit between wires had not occurred. Exposed conductors of the red and white wires each indicate arcing to the conduit, rather than to each other. Apparently the conduit had become hot enough to melt the wire insulation. Firemen discovered burned construction sawdust next to the concealed conduit that had been the source of smoke and smoldering. An AFCI would be expected to detect the sputtering arcs from the wires to the conduit and prevent this heating and the smoldering sawdust.

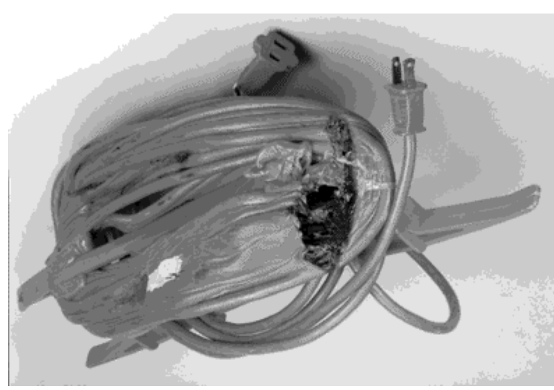

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Figure 1 - Damaged construction wire caused fire in nearby sawdust.

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Figure 2 - Wound cord insulation overheated with continuous operation with air conditioner load.

Wound wires overheated from normal current flow. Figure 2 is a second piece of evidence from the BFP in Cedar Rapids. The wound cord had apparently been connected to a window air conditioner which had been left unattended for a period of time. Normal current flow through the wound conductor had caused significant melting of the insulation, resulting in arcing between conductors. In this case, the unit was unplugged before a fire occurred. The OCPD had not opened because current was at normal load except for occasional bursts of line-to-neutral arcing.

An AFCI would not have prevented the melting of the insulation nor potential ignition of the insulation from heating. However, an AFCI would have been expected to detect the bursts of arcing and to have opened the circuit well before this degree of damage had occurred.

High resistance connection. Figure 3 shows a basement receptacle that had been used for 15 years as a connection for a water distiller. Although the ground connection is present, it was never connected to ground because it is an extension of a 2-wire circuit. There had apparently been a hot, high resistance connection that led to surface tracking from the ground bracket to each of the receptacle jaws. Evidence of moisture is also present. Indications are that a line-to-neutral arcing fault eventually occurred and the house filled with smoke. Eventually the circuit breaker opened the circuit. The 2 x 4 inch board to which the receptacle had been attached was blackened but had self-extinguished.

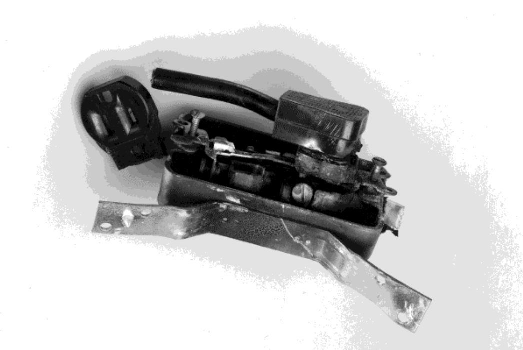
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Figure 3 - Line-to-neutral arc tracking across receptacle charred wood mounting surface.

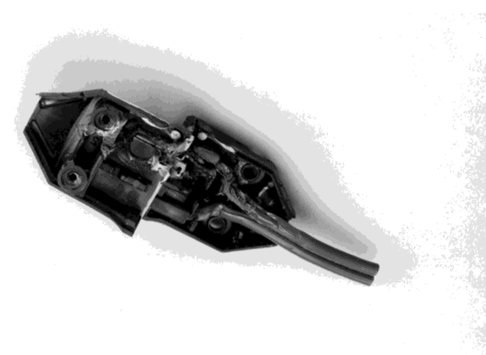
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Figure 4 - High resistance connection caused depletion of insulation.

Figure 4 shows an attachment plug that was connected to a space heater. Again, a high resistance connection has caused degradation of insulation of the plastic housing and the insulation on the cord. Notice that the cord insulation has melted away nearly causing a direct wire-to-wire (line-to-neutral) arcing fault where the wires come together. An AFCI would not detect the high-resistance connection and would not have prevented damage to the plug housing. However, it would have detected a line-to-neutral arcing fault as the damage increased.

These examples represent just a few of the many circumstances in which electrical fire causes involving arcs may arise. Recognize that arcing faults may occur in three circuit configurations: line-to-line (neutral), line-to-ground and in series with the load. Each of these configurations is protected to some degree by other currently available devices.

CONTRAST WITH TRADITIONAL OVERCURRENT PROTECTION

Protection against arcing faults is already provided to a very great extent by the OCPD, circuit breaker or fuse. Many electrical system faults involve arcing, especially where damaged insulation or equipment is involved in the fault. From the residential perspective, the time-current characteristic of Figure 5 is that of a 20 A circuit breaker. Any arc occurring for a time and current to the right and above the characteristic will be detected as an overcurrent condition and the circuit will be opened. Although the OCPD is intended to protect good conductors from becoming thermally damaged, a byproduct of this protection is to mitigate potential damage from arcing at the point of the fault. All circuits that complied with the National Electrical Code when they were installed have had this excellent protection all along.

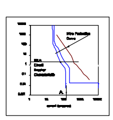

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Figure 5 - Time-current characteristic of a 20 A circuit breaker.

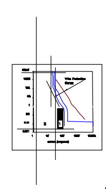

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Figure 6 - Regions not protected against arc-fault conditions.

In a study done by Underwriters Laboratories Inc. (UL) for the Electronic Industries Association (EIA), data shows that available short-circuit current at receptacles in residences ranges from approximately 75 A to 1650 A with an average of 300 A for 15 A branches and 467 A for 20 A branches. This data gives a good idea of the current levels available in branch circuits. [3]

Notice that the instantaneous opening current for the circuit breaker in Figure 5 begins at 120 A, shown at point A. This is about the lowest level at which an OCPD can be designed without nuisance operating on normal circuit occurrences such as transient inrush current to microwave ovens and burn out of tungsten light bulbs. Most circuit breaker designs in North America have an instantaneous opening level significantly above 120 A, perhaps a 300 A average. In all cases, a gap exists between the 75 A available level in the receptacle study noted above and the instantaneous open level for the OCPD. This gap is identified as region 1 in Figure 6.

Looking at points on Figure 5 below the continuous current rating of 20 A, no circuit protection exists. The circuit breaker must permit branch circuit current to flow. Normal transients and short time overcurrents are permitted to flow for brief periods at current levels just above the continuous current rating. Arc faults can exist in this region, region 2 in Figure 6, for long durations with no detection.

In reported fires of electrical cause, it is seldom that the OCPD has opened as found in an analysis by the author of data on 690 fires of electrical cause recorded by a major insurance company. This point indicates that present OCPDs are reasonably effective in mitigating fire causes for conditions under which they are designed to operate. That is, when an OCPD does operate to open, fires are most generally prevented. However, it also indicates that when hazardous, arcing conditions of time and current exist and are too low to cause operation of the OCPD, fires are occurring. Arc-fault protection in these presently unprotected regions 1 and 2 will mitigate fire causes.

CONTRAST WITH GFCI PROTECTION

If we look at the line-to-ground arc fault mode, we find that ground-fault circuit interrupter (GFCI) protection offers exemplary protection where it is applied for arc faults as well as any other type of fault to ground. GFCIs protect the circuit for any leakage current to ground 6 mA and higher. It is hard to imagine a form of protection that would be more comprehensive for the line-to-ground fault mode. In an evaluation of technologies available to address home fires done for CPSC, UL reported, AGround-fault interruption technology, due to the low-trip current levels that are possible, coupled with a fast response was shown to be very effective in interrupting arcing-fault currents to ground. This suggests that it should be combined with AFD [Arc Fault Detection] technology, since AFD technology does not require current to ground to operate@. [4]

One limitation to be aware of is that a ground path must be present for this protection to be effective. For example, many circuits in older homes are extensions of 2-wire circuits with no grounding conductor. A GFCI may be placed in these circuits, but it will not detect a fault to a conductor that is not grounded, even though it will be effective in protecting a person who is grounded. A second limitation is that receptacle GFCIs will protect only the cords and equipment connected to the receptacle. It would take a GFCI protecting the entire branch to protect fixed wiring in which a great many of the fire causing faults occur.

CONTRAST WITH GROUND FAULT PROTECTION

In residential systems, ground-fault protection other than the GFCI is not generally applied. However, there is another ground-fault protective device called an Equipment Protective Device (EPD) that has ground-fault protection at a higher sensitivity than the GFCI. The typical EPD operates with ground faults of 30 mA to protect sensitive equipment while the GFCI operates at 6 mA to protect personnel. As with the GFCI, the EPD will be effective in sensing arcing faults to ground.

INDUSTRY STANDARD

As products were developed, there was no industry standard to use as a guide. Literature and information was scarce to non-existent for details that related fire ignition conditions to arcs.

As it happened, three manufacturers of circuit breakers with prototypes of arc-fault circuit interrupters, separately and independently, contacted UL during 1993 and 1994 with inquiries regarding test requirements and the potential for future certification. Since there were no existing requirements nor even a basis for requirements, it was clear that such industry requirements would have to be developed. A Task Force of the National Electrical Manufacturers Association (NEMA) Circuit Breaker Section began in mid-1994 to develop a set of performance requirements. The Task Force produced a rough draft standard by December 1996 that is presently under review by UL. The expectation is that it will form a basis of a UL standard. Prior to publication of an industry standard, UL will consider learned input from a variety of sources including UL internal engineers and scientists and others associated with the industry.

OUTLINE OF INVESTIGATION

In the absence of a published standard, UL has used an internal outline of investigation to evaluate products recently submitted for the marking, ΑListed Circuit Breaker also Classified for Mitigating the Effects of Arcing Faults.@ Information from UL research, a literature search, research by manufacturers, and ideas from a cross section of experienced UL and manufacturer research people was collected for implementation in this outline of investigation. The tests specific to the arc detection function are in three categories:

1. Efficacy (arc detection)
2. Unwanted tripping
3. Operation inhibition

EFFICACY TESTS

Carbonized path tests. Every such product is required to demonstrate that it will detect arcing current at 5 and 10 amperes, at rated current of 15 or 20 amperes and at 150% of rated current. The pass criteria is that the circuit containing the arc must be opened before surgical cotton wrapped over the arc location is ignited or before the shortest time in which cotton ignited during UL research testing.

Point Contact Arc Test. In this test, samples of both SPT-2 cord and NM-B cable are used as test samples. With the test product connected to the test cord or cable, the cord or cable is cut using a steel blade much like a paper cutter. Available test current is 75, 100, 150, 200 and 300 amperes, except that the test will not be conducted above the instantaneous trip level of a circuit breaker, assuming the arc-detection function is integral with a circuit breaker. The test product is required to open the circuit within eight 1/2 cycle segments of arcing. The 1/2 cycle segments are counted because arcing is usually sputtering between normal load current and arcing current rather than continuous arcing.

UNWANTED TRIPPING TESTS

In this series of tests, the product is subjected to a series of tests with equipment or loading conditions that could look like an unwanted arc to some forms of devices. There are six loading conditions with multiple tests under each condition.

Loading Condition I - Inrush Current. These are conditions in which the initiating transient is high. Various configurations of tungsten filament lamps and capacitor start motors are test loads.

Loading Condition II - Normal Operation Arcing. These are conditions in which arcing is normal and expected. Brush motor, thermostatically-controlled contacts with heating appliance loads and a wall switch with lamp loads are test conditions.

Loading Condition III - Non-sinusoidal Waveform. These unusual waveform loads consist of electronic lamp dimmers, electronic variable-speed electric shop tools, computer switching-mode power supplies and fluorescent lamps.

Loading Condition IV - Cross Talk. This condition examines the ability of the test product to avoid operation when the arc is produced in an adjacent circuit under several configurations.

Loading Condition V - Multiple Loads. Under this condition, some of the non-sinusoidal waveform tests are repeated, but with the branch circuit loaded to 100% of its rating.

Loading Condition VI - Service Life. Tests with a wall switch and with a variable-speed shop tool are conducted again, but using test devices that have experienced considerable conditioning under load.

These tests represent a broad cross section of the toughest conditions the product will experience in the field. The number of field conditions and variations are unbounded and cannot all be anticipated by any test program. These tests will require any manufacturer to pay close attention to the possibility of unwanted operation in the product design. It is then expected that any serious manufacturer will consider other potential conditions that may uniquely affect the design in order to have a commercially viable product.

OPERATION INHIBITION TESTS

This series of tests evaluates whether the test product can distinguish an unwanted arc even in the presence of other loads or conditions in the circuit that might attenuate, hide or disguise the arc signal.

Tests for Masking. Selected loads from the Unwanted Tripping Tests are placed in series and then in parallel with an arc and with additional load. The AFCI is required to correctly detect the arc and open the circuit.

EMI Filter Tests. The product is required to correctly detect an arc in series and then in parallel with specified heavy filters.

Line Impedance Tests. The product is required to correctly detect an arc introduced within several construction configurations that could attenuate an arc signal.

Minimum Voltage Test. The product is required to demonstrate that it will detect arcs even if voltage falls below normal variances.

In addition to the comprehensive sets of tests for arc detection, the product is tested for performance during or after exposure to abnormal circuit conditions and environmental conditions under the draft standard.

These first products will not be marked as UL Listed Arc-Fault Circuit Interrupters. They are marked AListed Circuit Breaker also Classified for Mitigating the Effects of Arcing Faults.@ The distinction is that they have not yet been evaluated under an adopted set of AFCI requirements, requirements that are now undergoing evaluation by UL as stated above and may change before the AFCI category is officially promulgated and opened to the industry for Listing of AFCI products. That is, the UL category for AFCIs has not been opened for listing of products at this date. Until it has been opened, the program and marking discussed in this section are being used.

PRODUCTS

Arc-fault circuit interrupters integral with circuit breakers have been available in prototype form since about 1993 from several manufacturers. Prototypes of three manufacturers were first tested by an independent laboratory in 1994 under the CPSC study on residential electrical fires. [4] After several years of experimental field testing and subsequent design revisions, the first products were commercially introduced in late 1997. The ratings of these first products were 15 and 20 A, 120 Vac, 1-pole. Figure 8 is a photo of a commercial product in a circuit breaker. During 1998 we can expect to see AFCI products from several manufacturers emerge for residential applications.

All normal circuit breaker functions remain present for overcurrent protection just as it is presently provided. The AFCI function is supplementary. When an unwanted arc fault is detected, the circuit breaker trips and opens the circuit by means of its primary contacts. These circuit breaker and AFCI units can be installed in residential loadcenters or in panelboards interchangeably with the circuit breaker of the same type.

These 15 and 20 A, 1-pole ratings cover the most common residential circuits and those most likely to be mis-used. There is no reason that the technology will be limited to these ratings. As safety and commercial demands for other ratings emerge, products will undoubtedly be provided.

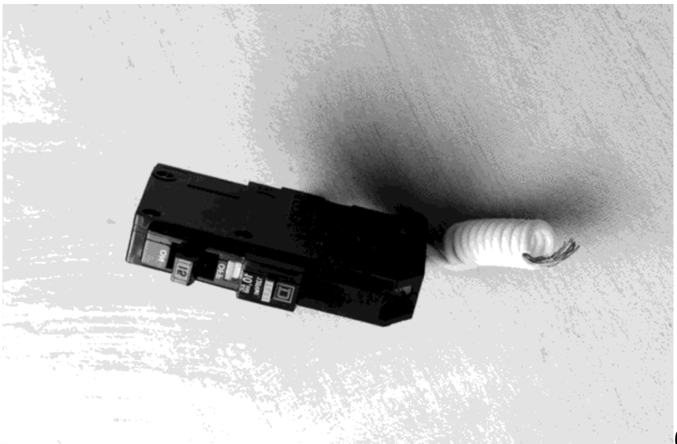
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Figure 8 - Circuit breaker incorporating AFCI function together with traditional overcurrent protection.

NATIONAL ELECTRICAL CODE

In the 1999 revision cycle for the National Electrical Code (NEC), there were three proposals to require the installation of AFCIs in all 15 and 20 A, 120 V circuits. These proposals acknowledged and were substantiated by several key points:

Uncontrolled electrical arcs are a significant cause of fires in residences.

The technology for arc detection is available in a viable product and has been shown to be effective in detecting arcs that could potentially cause fires.

. A substantial draft of an industry standard has been developed and is being used as a basis for third party certification of the products.

. Without enforcement of the installation of these devices, it is highly unlikely that they will be applied where they will do the most good in addressing fire causes.

At the time of the writing of this paper, NEC Panel 2 has accepted a revision that will require AFCIs in 15 and 20 A branch circuits serving receptacles in bedrooms with an effective date of January 2002. The panel comment indicates that the reduced requirement will Apermit these new devices to be introduced into the public domain on a gradual basis.@ [5]   Regardless of the outcome of these initial revision proposals, manufacturers have stated intention to provide the products for optional installation.

WHY FOR NEW CONSTRUCTION?

A fact that emerged during research regarding fire causes was that the preponderance of fires from electrical causes are in residences more than 10 years old. The question arose during evaluation of the proposals to revise the NEC concerning whether it is appropriate to require AFCIs in newly constructed residences. One fact to realize is that all new dwellings will eventually be older dwellings. Also, with the increase of available appliances and entertaining / computing equipment, the number of cord-connected devices is increasing significantly. The rating in watts for appliances is increasing. In other words, conditions making new homes susceptible to fire hazards not only continue to exist but in some instances are increasing, situations which will only worsen as new homes age.

Further, according to the 1987 Smith & McCoskrie CPSC report, the contributing factors to electrical distribution fires were: improper changes - 30%, aging - 14%, improper use - 13%, inadequate capacity - 12%, improper initial installation - 17%, faulty product - 9%. [2] As any residence ages, the probability of fire resulting from any of these factors increases. The AFCI is designed and intended to detect arcing that may arise due to aged, damaged or improperly installed wiring and equipment.

SUMMARY

AFCI products have the capability to mitigate arcing fault causes of fires in residences. Demand will determine applications beyond the 15 and 20 A, 1-pole ratings at 120 V for which products are being introduced.

REFERENCES

1. John. R. Hall, Jr., AThe U.S. Fire Problem Overview Report Through 1994,@ (National Fire Protection Association, April 1996).

2. Linda Smith and Dennis McCoskrie, AResidential Electrical Distribution System Fires,@ (U.S. Consumer Product Safety Commission, December 1987).

3. *Fact-Finding Report on An Evaluation of Branch-Circuit Circuit-Breaker Instantaneous Trip Levels*, (Underwriters Laboratories Inc., October 25, 1993).

4. *Technology for Detecting and Monitoring Conditions That*

Could Cause Electrical Wiring System Fires, contract number CPSC-C-C-94-112, (Underwriters Laboratories Inc., September 1995).

5. *National Electrical Code Committee Report on Comments - 1998 Annual Meeting*, (National Fire Protection Association, Quincy, MA, 1998).